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Shielding Design Basis and its Calculation of High Energy Medical Linac Installed in Bangladesh Atomic Energy Commission, Bangladesh

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Abstract High energy medical linac from Varian Medical Systems of model Clinac iX is installed in Bangladesh Atomic Energy Commission with dual photon energies (15 MV and 6 MV) and five electron energies upto 18 MeV. This machine is used to treat cancer patients either in electron or photon mode depending on the position of the malignant tissue. As the particles energies are in MeV range, special measures are taken into account for designing linac bunker. In this study, maximum photon energy is considered for shielding design. Other two particles i.e., electron and neutron are not considered due to their low penetration depth. As physicists the aim for us is to consider and calculate the shielding so that to protect the people and the stuff. Protection is required against three types of radiation such as, primary radiation (from the patient), scattered radiation (from the patient) and leakage radiation (from the linac head). To save the radiation worker from these three types of radiations, primary wall and secondary wall thickness, primary wall width and roof thickness are calculated. These calculations are done by empirical equations known as NCRP calculations using data in tabular form. These empirical equations are similar to those developed by Mutscheller. The primary and secondary barrier thickness for 15 MV and 6 MV photons are 2.84 m, 2.31 m and 0.93 m, 0.83 m respectively. Radiation survey reports are found to be below 10 $\mu Svhr^{-1}$ at six different locations for different gantry positions. This paper reveals what measures have been taken to protect the occupational workers and public from linac radiation hazards.

Keywords Medical Linac, Primary Barrier, Secondary Barrier, Neutron Production

1. Introduction

High energy medical linac (linear accelerator) from Varian Medical Systems of model Clinac iX is installed in Bangladesh Atomic Energy Commission with dual photon energies (15 MV and 6 MV) and six electron energies upto 18 MeV. This machine require high shields due to 15 MeV photon. The NCRP defines “shields” as a physical entity interposed between a source of ionizing radiation and an object to be protected such that the radiation level at the position of that object will be reduced. In general, the higher the kinetic energy of the incident particle, the greater yield and number of types of secondary radiations [1]. In case of electron beam, bremsstrahlung photons dominate the secondary radiation field for all incident electron energies. During photon beam, radiation directly or indirectly strikes the primary wall and secondary wall. The primary barrier is the wall into which the beam is incident directly and all other barriers are considered secondary [2]. NCRP report no. 49, 51 and 79 represent the current method for calculating the thickness of the primary and secondary barrier of x-rays. Report no. 49 is for photon energies up to 10 MeV, whereas, report no. 51 is used for higher photon energies. In report no. 70, detailed neutron shielding information for high energy x-rays interaction is mentioned. The design of mazes for photons and neutrons are first time uttered in NCRP report no. 51 and additional information about mazes used to attenuate neutrons are provided in report no. 79. The present shielding method relies on data, in either tabular or, graphical form in conjunction with empirical equations [3]. These empirical equations are similar to those developed by Mutscheller. In this paper, calculations are done using data in tabular form.

Shielding is designed depending on energy of the photon. This photons can be altered through collisions and uniform translation, in consequence, continuous slowing down, decay or the introduction of new particles. Directly ionizing radiation interacts very strongly with shielding media and is, therefore, easily stopped [1]. As physicists the aim for us is to consider and calculate the shielding so that to protect the

people and the stuff. Protection is required against three types of radiation such as, primary radiation (from the patient), scattered radiation (from the patient) and leakage radiation (from the head). For high energy LINAC facility in a hospital, the proper design is needed to optimize the wall thickness. Shielding wall usually consists of concrete, and iron plate is sometimes added in concrete to decrease the wall thickness. Moreover, linac orientation, width of primary barriers, joints and shutter bolt positions, nibs, ducts, lintels, wall height and primary ceiling barriers, laminated walls, direct doors, ground shine these are the practical consideration for designing linac bunker [4]. The main basis of shielding design is that the equivalent dose received by an individual does not exceed the applicable maximum permissible value. Annual dose limits according to BSS schedule and ICRP report 60, occupational exposure is 20 mSv averaged over five consecutive years and 50 mSv in a single year. For quality assurance, one tenth of maximum value is taken into account for shielding calculation. So, maximum permissible dose (P) should be 5 $mSvyr^{-1}$. According to Bangladesh Atomic Energy Regulatory Act 2012 and Nuclear Safety & Radiation Control Rules 1997, P value should be 0.1 $mSvyr^{-1}$. Our bunker shield for linac facility is made of concrete. Shielding calculation formulae for the above three types of radiation are as follows [5]:

Primary barrier

Transmission factor for primary barrier

$$B_{pri} = \frac{P \cdot d^2}{WUT} \tag{1}$$

Secondary barrier

Transmission factor due to scattered radiation

$$B_s = \frac{P}{\alpha WT} \cdot \frac{400}{F} \cdot d^2 \cdot d'^2 \tag{2}$$

And for leakage radiation

$$B_l = \frac{P.d^2}{0.001WT} \quad \text{(Therapy above 500 kVp)} \tag{3}$$

Where, W→ Workload, U→ Use factor, T→ Occupancy factor which is fraction of time a particular place is occupied by staffs, or public and ranges from 1 for all work areas and 0.06 for toilets and car parks, d→ Distance from the linac target to the far side of the barrier, d′→ Distance from the patient to the point of interest and P→ Maximum permissible dose equivalent.

The required number (n) of TVLs is calculated as

$$n = \log(1/B) \tag{4}$$

And the barrier thickness ($t_{barrier}$) is given by:

$$t_{barrier} = TVL_1 + (n-1)TVL_e \tag{5}$$

Where, the first and equilibrium TVLs are used to account for the spectral changes as the radiation penetrates the barrier. The values of TVL_1 and TVL_e are taken from NCRP values [6].

Width of Primary Barrier

If the beam is projected on the barrier from X meter away, the maximum width at the barrier W′ is given by W′= 0.566X [3]. At the junction between the wall and the ceiling, there some additional thickness needed as one foot in both sides. So previous equation should be modified as follows [3].

$$W' = 0.566X + 0.61 \tag{6}$$

Door Design

High-energy x-ray beams (>10 MV) is contaminated with neutrons [5]. Considering this phenomenon, the door is designed in the following any one of the two patterns:

A few inches of a hydrogenous material such as polyethylene is sandwiched between two layers of lead in the door to thermalise the neutrons. First and second lead layers in the door are used to attenuate γ rays from consecutive end γ reaction. On the other hand, two adjacent layers made of 5% boronated polyethylene and lead covered with steel casing is used for neutron door. The polyethylene (high H content) slows (moderates) the fast and intermediate energy neutrons to thermal energies. The 5% boron absorbs the low energy neutrons (high cross section for thermal neutron absorption). Lead absorbs the photon that results from the (n, a) and capture gammas (from maze ceiling, and floor).

2. Methods

2.1. Primary barrier

Workload (W) is a measure of the radiation output measured in Gy for linear accelerators. Average dose ranges at isocentre is assumed to be 2.5 $Gypatient^{-1}$. For 5 working days in a week W = 3.25 × 10^7 $mSvyr^{-1}$ in case of photon radiation. Usually, it is a gross over estimation and for quality assurance, workload measurements increased by 20%. Thus, W (by 20% increment) = 3.9 × 10^7 $mSvyr^{-1}$. Use factor U = 1, Occupancy factor T = 1, Distance from the linac target to the far side of the barrier d = 7 m and P = 0.1 $mSvyr^{-1}$. Putting the above values in Eq. 1, B value is 1.26 × 10^{-7}.

2.2. Secondary barrier

Parameters are used for primary barrier calculation are same for secondary barrier. Here, α is the ratio of the scattered radiation at 1 m from the scattering object (patient) to the primary radiation at 1 m. Its typical value for 90º scatter is in between 10^{-4}–10^{-3}. In this calculation, it is taken as 0.6 × 10^{-3} [3]. F is the actual field size at the mid-depth

position at 1 m of the patient is taken as 40 × 40 cm^2. d^2 is the square of the distance from the source to the scattering volume (patient) is taken as 1 and d′ is the distance from the patient to the point of interest is taken as 5.5 m. Putting the above values in Eq. 2, B_s value is 0.000039.

2.3. Width of Primary Barrier

Maximum beam size for most accelerators at one meter away from the target is 40 × 40 cm^2. At 45° gantry angle from the zero position, the maximum horizontal width of the beam is the diagonal dimension of the 40 × 40 cm^2 field, which is 56.6 cm [3]. The projected beam distance X is taken as 3.4 m and putting this value in Eq. 6 primary barrier width is found.

2.4. Roof Thickness

Barrier transmission factor for roof is calculated from Eq. 1. Where, occupancy factor T = 1/16 for uncontrolled area, use factor U = 1/4 for vertical up direction and distance d from the target to 0.305 m above the shield in meter is 6.325 m. Figure 1 represents the layout of 15 MV linac bunker.

3. Results and Discussions

3.1. Bunker Shielding Calculation

Values are calculated from empirical formulae known as NCRP calculation is presented in tabular form in table 1. It is assumed that roof and primary layer thickness should be the same. But in calculation, roof thickness is slightly different from primary layer due to the variation of occupancy and use factor values. The point of interest for roof thickness calculation, 0.305 m above the shield, is considered to be uncontrolled area. If the access to the roof is prohibited and there are no nearby buildings, the IDR (instantaneous dose rate) at the surface of the roof upto a maximum of 2 $mSvh^{-1}$ is acceptable in case of skyshine. Physically thin wall made of steel plate or lead blocks may create ground shine beneath the wall, which add exrta dose rate transmitted through the wall. In that case, additional shielding on the floor at the foot of the wall may be necessary to reduce the ground shine to an acceptable dose rate [4]. Our primary and secondary barrier thickness for 15 MV are 3.60 m and 1.40 m respectively. This large thickness minimizes the probability of ground shine. Concrete density is considered to be 2.35 g cm^{-3}. From practical experience, sometimes concrete mixing ratio is not maintained properly. So, our designed thickness values are more than theoretical values. In designing a room, one of the choices to be made whether to use a long maze or a direct shielded door [7]. The length of the maze for energies higher than 10 MV is not done in this calculation. Our designed bunker having a long maze 12 × 2 m^2 as well as shielded door give the more confirmation from unwanted exposure outside the door.

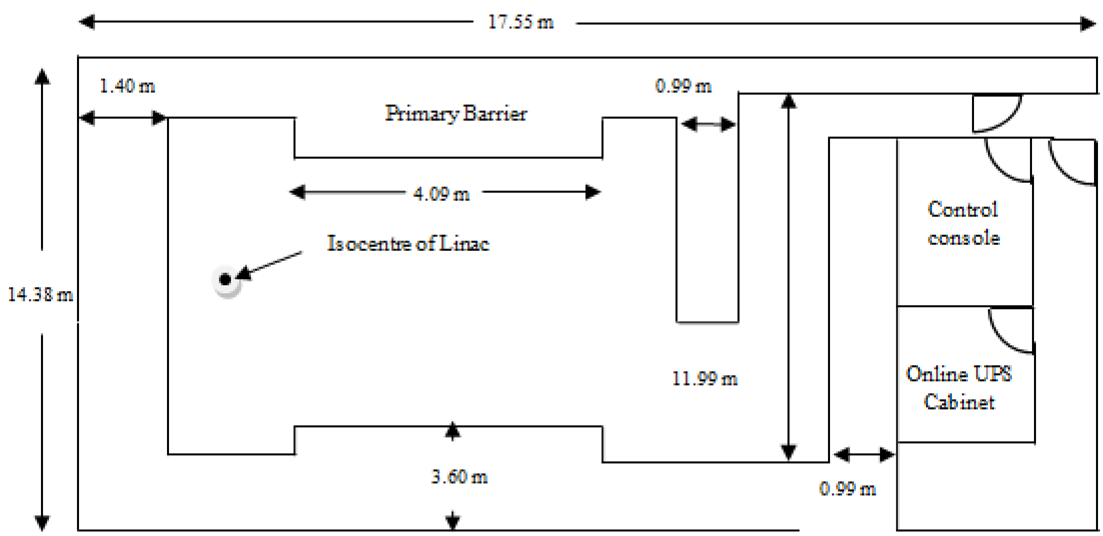

Figure 1. Layout of 15 MV medical linear accelerator bunker

Table 1. Theoretical and designed thickness values of bunker for 6 MV and 15 MV photon

Parameter name	Energy	Needed value (from calculation in meter)	Our designed value (in meter)
For primary barrier	6 MV	2.31	3.60
	15 MV	2.84	
For secondary barrier	6 MV	0.83	1.40
	15 MV	0.93	
Roof thickness		2.20	3.66
Width of primary barrier		1.93	4.09

Table 2. Photon dose rate in μSvh^{-1} with field size 40 × 40 cm^2 and dose rate of 600 MU/min at normal treatment distance for six different locations for different gantry positions

Gantry angle (°)	Primary wall 1	Primary wall 2	Secondary wall (gantry side)	Control console	Door location	Roof
0	--	--	2.5	--	--	--
90	0.17	--	1.2	0.22	0.31	--
180	--	--	--	--	--	0.2
270	--	0.25	--	0.24	4.05	--

Table 3. Neutron dose rate and beta activity with field size 40 × 40 cm^2 and dose rate of 600 MU/min at normal treatment distance for three different locations for different gantry positions

Gantry angle (°)	Neutron dose in μSvh^{-1}			Beta activity in $Bqcm^{-2}$		
	Operator position	Wall surface of console room	Door	Operator position	Door (at gonad level)	Door (at upper side)
0	--	--	--	--	--	--
90	--	--	4.23	0.26	2.01	1.57
180	--	--	--	--	--	--
270	1.20	1.27	1.27	--	2.10	3.35

3.2. Radiation Survey for Photon

The radiation survey measurements are carried out all around the installation at different locations. For radiation level measurement, a calibrated gamma dose rate meter of model: Graetz X5 DE# 53079 (Germany made) meter is used. Its background radiation level is 0.20- 0.23 μSvh^{-1}. Linac is operated in maximum available dose rate. All measurements are performed with the maximum achievable field size 40 × 40 cm^2. For each location, measurement is taken at the point where the survey meter reading is maximum [8]. Radiation levels are measured at seven locations, that is, primary wall 1, primary wall 2, ceiling, secondary wall (gantry side), secondary wall (couch side), door location, and the control console. At each point, measurement is taken with gantry angle where the dose is predicted to be maximum. The measured data are presented in Table 2.

3.3. Radiation Survey for Neutron and Beta

Concrete barriers designed for high x-ray shielding are sufficient for protection against neutrons [5]. But near the door, there is some probability of getting neutron dose. So door is made by two adjacent layers of boronated polyethylene, and lead covered with steel casing with dimension (1.92 m × 2.12 m × 0.06 m). The radiation field at the door is a mixture of fast and thermal neutrons, and neutron-captured gammas. The neutron-captured gammas are emitted from captures in the maze wall as well as the door [9]. Production of photoneutrons is increased with field size and is decreased by distance from isocenter [10]. Depending on this phenomenon, survey is done for both neutron dose and beta activity is shown in table 3. Maximum value of neutron dose is found at door which is less than 10 μ$Svyr^{-1}$. Survey meter of model: REM 500 and S/N: 384 with background reading 0.0 μ$Svyr^{-1}$ is used for neutron survey. Contamination monitor of model: DKS-96 and S/N: 0282003 (Made in Russia) with background reading 0.35-0.37 $Bqcm^{-2}$ is used for surface beta activity. For accurate neutron dose measurement, passive dosimeter like TLD is better than active dosimeter [11]. Because, at high energies, neutron dose fluctuate with a large extent. So, active dosimeter is not convenient for neutron dose measurement.

4. Conclusion

The shielding requirements for a linac facility vary from energy to energy. Linac bunkers are designed to prevent unintentional exposure of staff, patients and the public. The minimum distance to the occupied area from a shielded wall is assumed to be 0.3 m. Our designed thickness values are more than theoretical values. This is due to practical experience and consultation with other linac facilities shielding experts. The scattered photons may exit through a door in the room unless that door is hidden by a maze. Our long maze prevents the scattered photons to escape from the bunker by a significant amount. At high energies, neutrons scattering are multiple times compared with that of photons. In addition with long maze, borated polyethylene panel of 12 mm thickness coated with steel cover is used as a neutron shielding door.

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